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The Study on the Behavior under Dynamic and Static Analysis of Reinforced Concrete Core Wall-Perimeter Steel Frame Hybrid Structure, Part I

RCコア壁付き鉄骨骨組の動的および静的挙動に関する研究

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We study the behavior under dynamic and static analysis of reinforced concrete core wall-perimeter Steel frame hybrid structure with static pushover analysis and incremental dynamic analysis(IDA). IDA is a parametric analysis method that has recently emerged in several different forms to estimate more thoroughly structural performance under one or more ground motion records, each scaled to multiple levels of intensity. The results with IDA analysis and the conventional static pushover analysis are studied, in addition, the amplificatory ratio γ under IDA and static analysis are discussed. We find that the bebaviors of the frame and core wall are very much different under dynamic and static analysis. The ratio γ has a great connection with the intensity of the input ground motion, the stiffness distribution and especially the location along the building. We should pay attention in practical design work.

Keywords : Reinforced Concrete, Core Wall, Steel Frame, Hybrid Structure, Icremental Dynamics Analysis, Pushover Analysis
鉄筋コンクリート，耐震壁，鉄フレーム，混合構造，増分時刻歴応答解析，荷重増分解析

1. Introduction

According to the general knowledge, a hybrid structure means that the structures are combined by at least two component parts of different materials. The combination is supposed to obtain the excellent performance after mixing two or more kinds of structure systems reasonably which simplex structure system doesn't have.

The hybrid structure is mostly applied to high-rise and extremely high-rise buildings. It varies in forms and names for the combination of materials, cross sections and structure forms. There are three kinds of hybrid structures in common use.

The first is Concrete-Filled Steel Tubes Column Systems (CFTs). CFTs offer a number of advantages when used in seismic-resistant frames. The concrete infill confined by the steel tubes provides increased axial stiffness and load capacity. The concrete fill also restrains local buckling of the tube, and increases member ductility, while permitting more slender steel elements.

The second is Reinforced Concrete/Steel Reinforced Concrete Column Systems (RCs/SRCs). The RCs systems are moment frames consisting of RC columns and steel beams. They provide excellent stiffness with RC columns and energy dissipation capacity through steel beams. As opposed to conventional steel or RC moment frames, the problems associated with connections are greatly reduced, and the RCs frames are generally more economical than the purely steel or RC moment frames.

The third is Reinforced Concrete/Steel Reinforced Concrete Hybrid Wall Systems. Hybrid wall systems consist of RC or SRC walls to provide resistance against lateral forces and steel-beam and column-frame systems to support the gravity loads. Most of the lateral strength and stiffness to the system is provided by the walls. The floor system, in addition to supporting the gravity loads, also serves to transfer the lateral forces to the walls [1).

The focus of this paper is on the third one. This efficient hybrid structure system is obtained when reinforced concrete core walls are used in conjunction with steel perimeter frames. For low-to-moderate-rise buildings, up to 25 to 30 storeys, the core can be used to provide a majority of the lateral force resistance for earthquake and wind. For taller buildings, the use of dual systems is more common, where the perimeter frames are engaged with the core. The hybrid structure system has large lateral stiffness in each direction, the perimeter frames mainly support vertical loads and some part of horizontal loads which are distributed based on the lateral stiffness of dual systems. The lateral stiffness of reinforced concrete core wall accounts for more proportion of the total

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stiffness, thus the core walls resist more horizontal loads. Specially according to yield strength of substructure, the yield strength of reinforced concrete core walls is much smaller than that of perimeter frames, so the core walls have relatively redundant stiffness but insufficient strength which reduce its anti-earthquake performance. The plastic hinges of the hybrid structure appear in the core walls under severe earthquake, and this kind of plastic hinge mechanism is very harmful to the structure system. With excessive deformation and damage in the core walls, the whole structure or its sub-structure would lose stabilization and collapse. The successful performance of such hybrid structural systems depends on the adequacy of the primary individual components which are the core walls, steel frames, and frame-core connections [2]. In this paper, the authors mainly think about finding the rule of the storey shear force distribution in different proportion of core walls and perimeter frames, especially research the effect of incremental dynamic analysis on seismic load.

2. Analysis model and method of hybrid structures

2. 1 Analytical plan

The floor plan of a representative hybrid building using this structure system is shown in Fig.1. The walls may be reinforced conventionally with longitudinal and transverse reinforcement, or may include embedded structural steel boundary columns in addition to conventional reinforcing bars.

For simplifying the analysis procedure, we can turn the 3-dimention model into 2-dimention planar model that is shown in Fig.2. The pure frame portion and the frame with core walls portion are linked by link elements which have large rigidity with two pin joints that can transfer load and deformation [3]. Because of the limits of our analysis program, the problem is how to compute the core-wall in our model. In Japan, there is a conventional method to simulate the shear wall with the equivalent diagonally-braced frame.

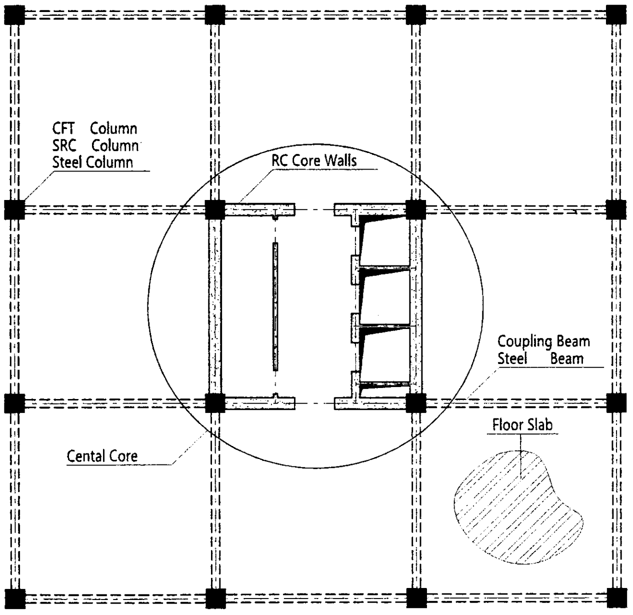


Fig.1 Floor plan of reinforced concrete core wall-perimeter frame system

2. 2 Conventional Equivalent Structure Method for Shear Wall

The equivalent method is mentioned in Masafumi Inoue and Masahide Tomii's paper named Method of estimation of rotational rigidity of the corner connections of framed shear walls for their equivalent diagonally-braced frames [4].

The cross sectional area, A_b, of the braces in the equivalent frame is determined by equalizing the shear rigidity of the shear wall to that of the equivalent frame. The drift, δ_{ws} , due to shearing deformation of the shear wall is given by Eq. (1)(see Fig. 3 (a)).

$$\delta_{ws}=\frac{k'_w h}{GA_w}X=\frac{2(1+\nu)k'_w h}{EA_w}X \qquad (1)$$

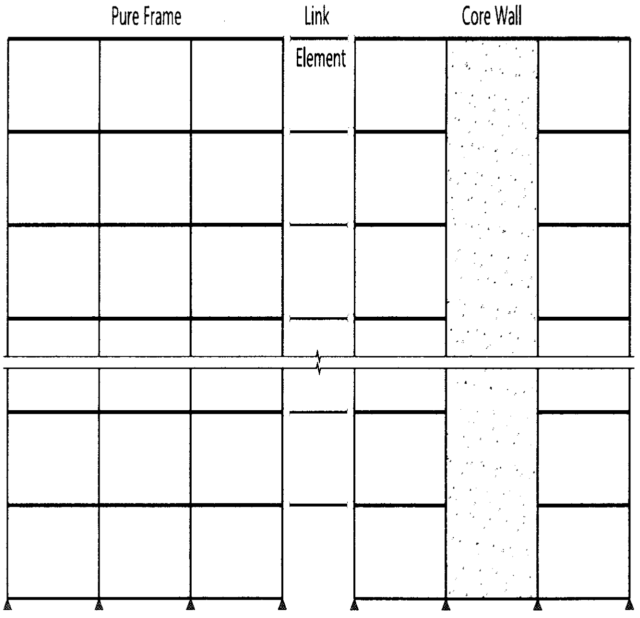
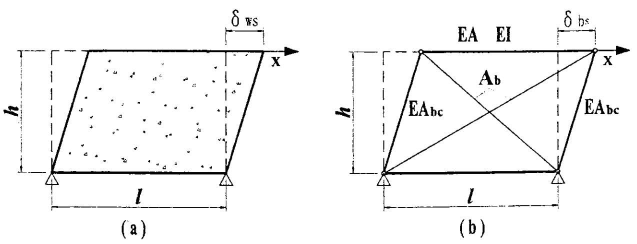


Fig.2 Planar model of hybrid structural system



(a) (b)

Fig. 3 Model to determine the sectional area of the braces in equivalent frame where

E: Young's modulus

v: Poisson's ratio

k_w': shape factor for shearing deformation of shear wall

G: shear rigidity $[=E/2(1+v)]$

h: story height

A_w: horizontal sectional area of wall

X: horizontal force

The drift, δ_{bs}, of the equivalent frame is given by Eq. (2)(see Fig. 3 (b))

$$\delta_{bs} = \frac{1}{EA_b} \cdot \frac{(h^2+l^2)^{1.5}}{2l^2} X \qquad (2)$$

where

l: distance from center to center of edge columns

The cross sectional area, A_b, of each brace in the equivalent frame is given by Eq. (3) when δ_{ws} and δ_{bs} respectively given by Eqs. (1) and (2) are made equal.

$$A_b = \frac{G}{E} t \frac{(h^2+l^2)^{1.5}}{2k_w' lh} \qquad (3)$$

where

t: thickness of wall

The cross sectional area, A_{bc}, of columns in the equivalent frame is determined by equalizing the flexural rigidity, EI_w, of the horizontal sectional area of the shear wall to the flexural rigidity, EI_b, of the equivalent frame. The EI_w is given by Eq. (4).

$$EI_w = E\left[2\left\{I_{wc} + A_{wc}\left(\frac{l}{2}\right)^2\right\} + \frac{tl'^3}{12}\right] \qquad (4)$$

where

I_{wc}: moment of inertia of the cross sectional area of the edge columns of a shear wall

A_{wc}: cross sectional area of each edge column of a shear wall

l': clear span of the boundary frame of a shear wall

The EI_b is given by Eq. (5).

$$EI_b = 2EA_{bc}\left(\frac{l}{2}\right)^2 \qquad (5)$$

The A_{bc} given by Eq. (6) is obtained by equalizing EI_w and EI_b respectively given by Eqs. (4) and (5).

$$A_{bc} = \frac{4}{l^2} I_{wc} + A_{wc} + \frac{tl'^3}{6l^2} \qquad (6)$$

The equivalent frames of shear walls are determined by using the values of A_b and A_{bc} respectively given by Eqs. (3) and (6).

2. 3 Material hysteresis property

Two types of Steel materials are used in our analysis model, SN490 is used for H shape Steel beam and reinforced bar in concrete and BCR295 for □ shape

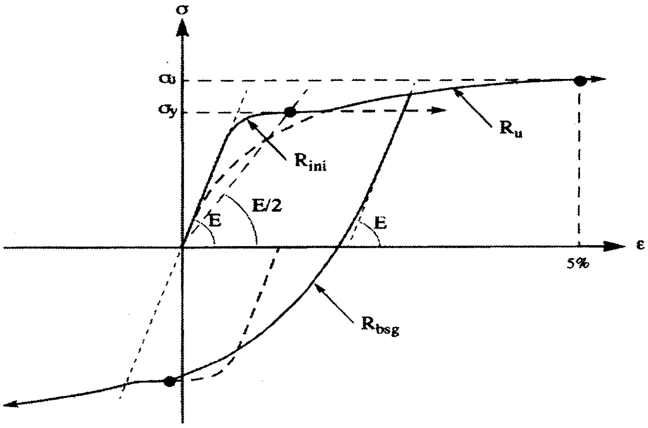


Fig.4 Stress-strain relation for steel

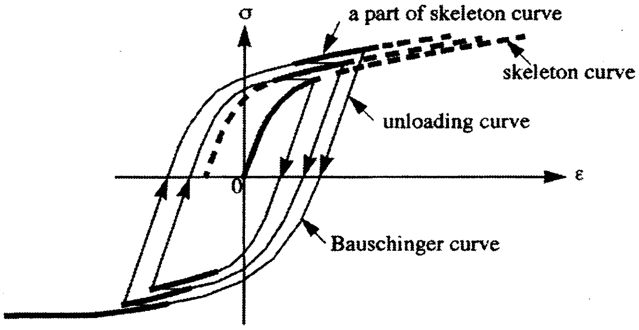


Fig.5 Akiyama and Kato model

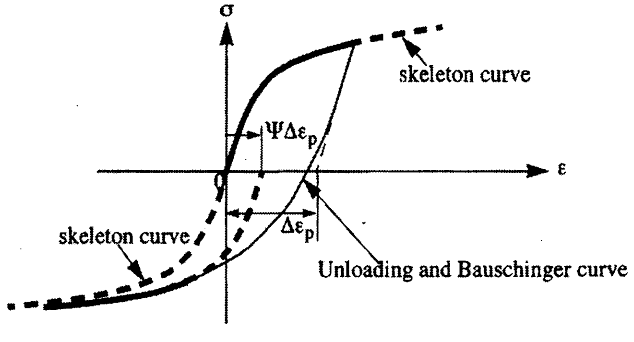


Fig.6 Ohi's rule for skeleton part moving

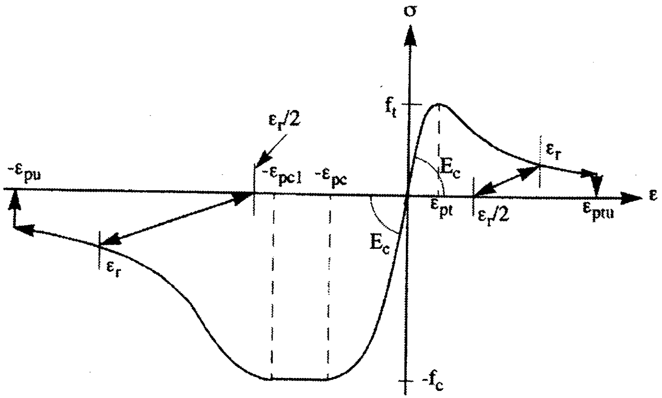


Fig.7 Stress-strain relation for concrete

steel perimeter columns. The following figs have showed their hysteresis property and stress-strain relation.

2. 4 Analytical model

The analytical model is shown in Fig. 8, the numbers on the top are the mass for each storey. The section of each member is shown in Table. 1, 10% and 5% mean the reinforced bar ratio in concrete sections. The average mass is 1.0ton/m^2, the story height is 3.6m except 4.0m at the first story, the region coefficient equals to 1.0, the standard base shear coefficient equals to 0.2 at first level and 1.0 at second level. The static pushover load distribution equals to Ai distribution according to the Japanese code (Fig.9) $^{5)}$. The seismic waves of the ground motion records for the incremental dynamic Time-History analysis are LA1-LA20(FEMA) (Fig. 10). Newmark β method is used in the dynamic analysis, the damping factor of the first and second mode shape equals to 0.03, the factor β equals to 0.25. The PGV of the seismic waves from LA01 to LA20 is equal to 10, 20, 30, 40, 50, 60,70, 80, 90, 100kine.

The first period T_1=0.34s, and second period T_2=0.16s.

3. Analytical results and discussion

3.1 A rule of comparison between static and dynamic responses

When we compare the difference of the responses of the structure between dynamic analysis and static pushover analysis, the key question is how to compare, we should make a rule to compare the result. So we define a rule as follows,

1. Find the center of the Ai distribution Load (Get the storey number as shown in Fig. 9),
2. Find the maximum deformation of this storey under the Dynamic Time-History analysis,
3. Find the step of the static pushover analysis that

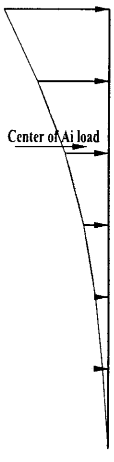


Fig.9 Ai distribition Load

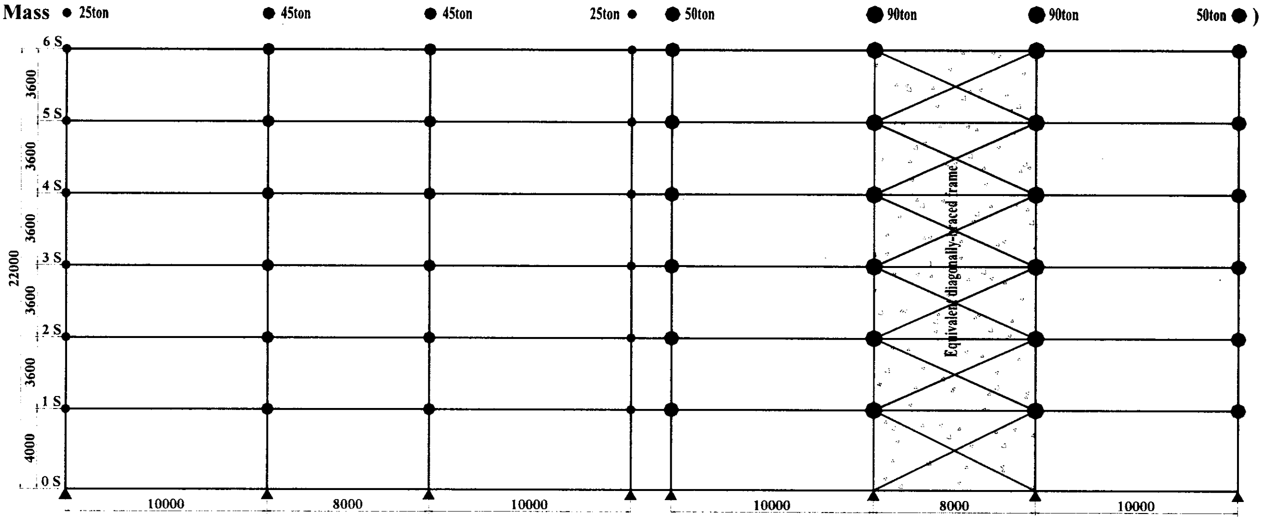


Fig. 8 Analytical model with equivalent diagonally-braced frame

Table. 1 The section of the analytical model

	□-Steel Column		H-Steel Beam			
	H(mm)	t(mm)	H(mm)	W(mm)	t_1(mm)	t_2(mm)
6S	450	18	700	200	9	21
5S	450	18	750	300	16	26
4S	450	18	750	300	16	26
3S	450	18	750	300	16	26
2S	450	20	800	300	18	26
1S	450	20	800	300	18	26
0S			1100	400	20	48

	□-Eq-W-Column			□-Eq-W-Brace		
	H_1(mm)	H_2(mm)	u	H_1(mm)	H_2(mm)	u
6C	1030	1030	10%	970	970	5%
5C	1030	1030	10%	970	970	5%
4C	1030	1030	10%	970	970	5%
3C	1030	1030	10%	970	970	5%
2C	1030	1030	10%	970	970	5%
1C	1030	1030	10%	970	970	5%

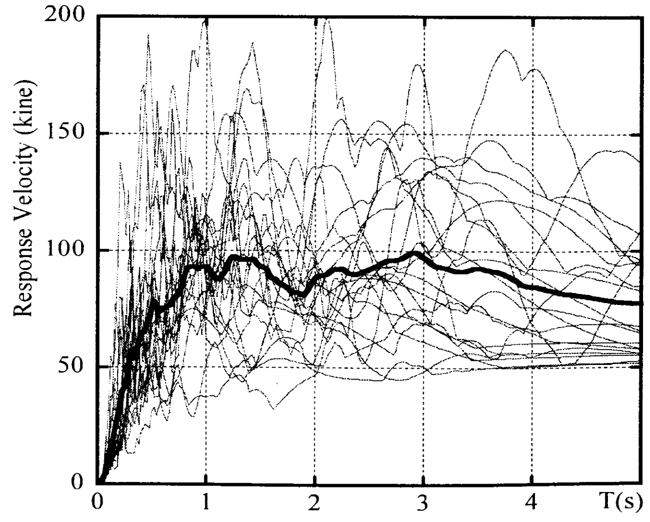


Fig.10 Spectrum of the earthquake LA1-LA20

the deformation of this storey probably equals to the deformation we find in step 2.

From the rule, we get the state that is able to be discussed as shown in Fig. 11 ⁶⁾. The thin dash line means the result for each seismic wave under Time-History Analysis, the wide line means the average of the result, and the wide dash line means the result for static pushover analysis, we can see that the profile deformation in different analysis perfectly match. So in this state, we can discuss the storey-drift angle, shear distribution, etc between dynamic and static analysis.

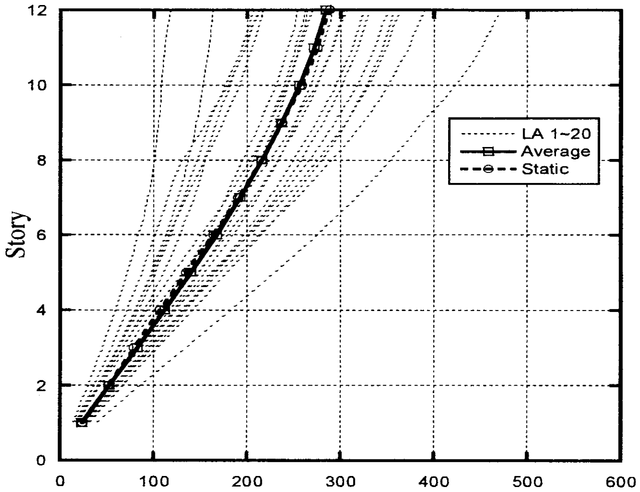


Fig.11 Horizontal deformation

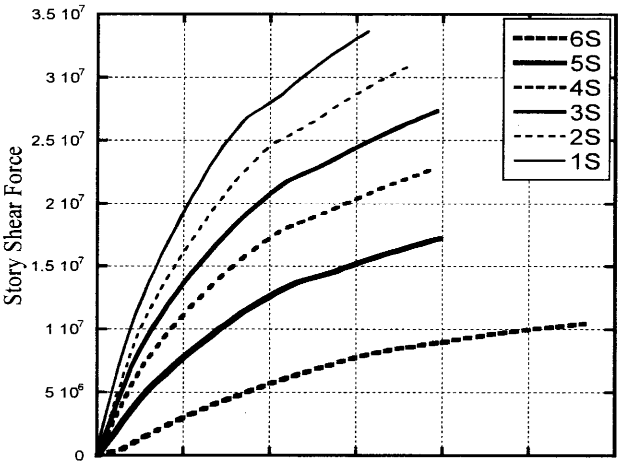


Fig.12 Static Pushover Curve

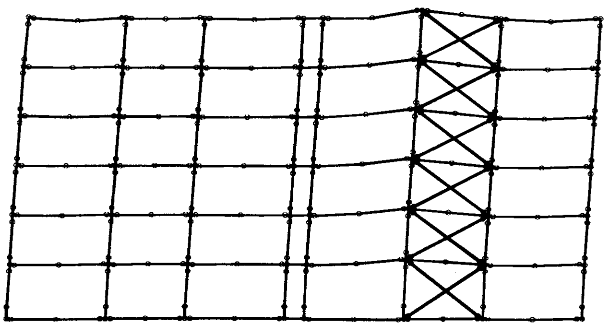


Fig.13 Analytical model deformation shape

3.2 Results discussion

Our analytical model is a hybrid structure including perimeter steel frame and reinforced concrete

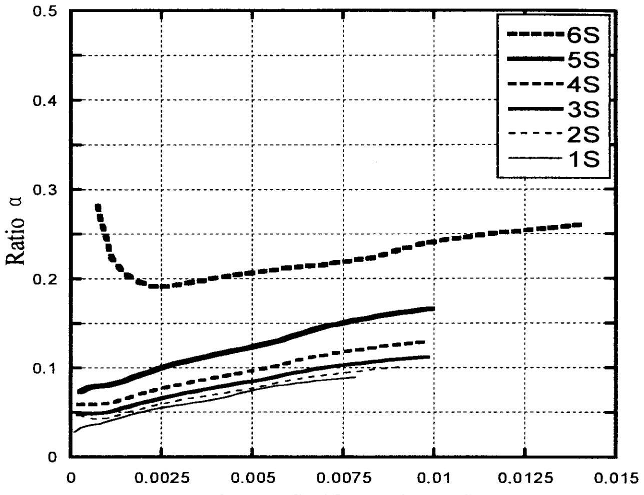


Fig.14 The shear force proportion of frame columns

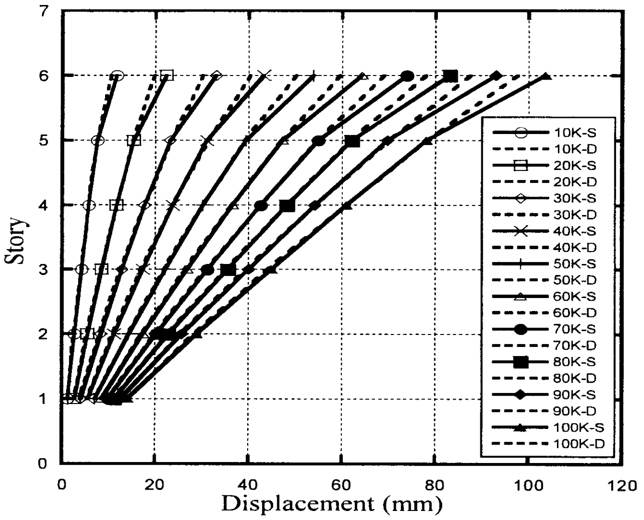


Fig.15 The max storey displacement of different intensity

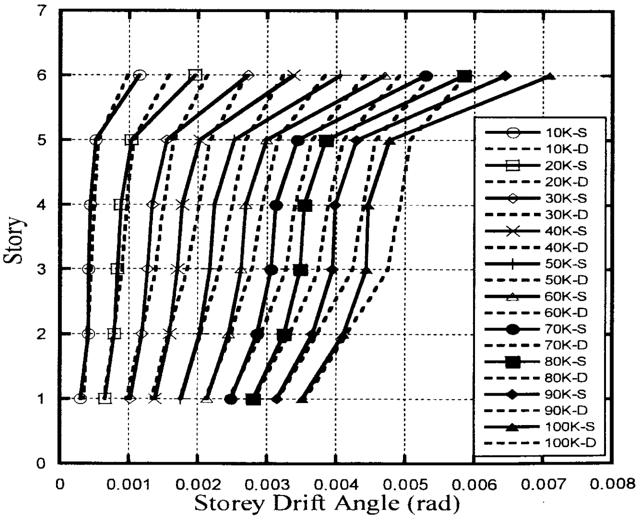


Fig.16 The storey drift angle of different intensity

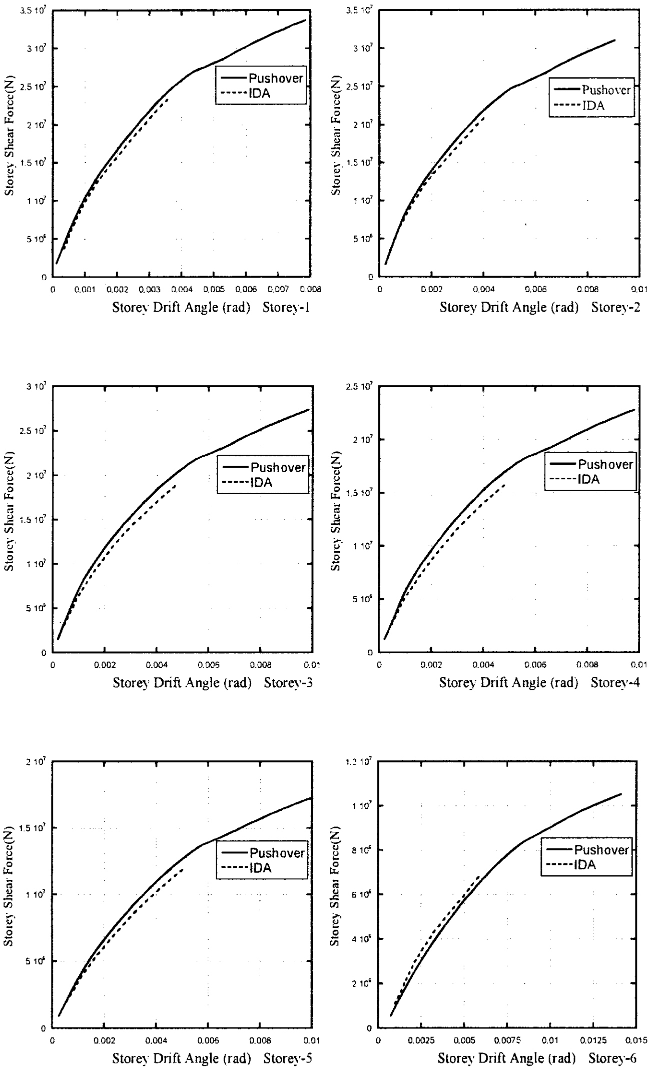


Fig.17 The interstorey shear force

core wall, each of them has its own property and deformation pattern. For example, pure frame has a shear deformation pattern and reinforced concrete core wall has a bending deformation pattern, especially the core wall has a large stiffness but a very smaller deformation than pure frame, when shear wall begin to crack, the frame is still elastic, when frame begin to yield, the shear wall almost reach its ultimate status.

The behavior of this kind of hybrid structure is very complex, only static pushover analysis can't describe its behavior clearly, so dynamic analysis is needed. We modify the PGV equal to 10kine, 20kine, 30kine, 40kine, 50kine, 60kine, 70kine, 80kine, 90kine, and 100kine for each earthquake waves to change the intensity of the input ground motion, just like a dynamic pushover analysis. So we can think about the behavior of the hybrid structure in different deformation status $^{7)}$.

Fig. 14 shows the shear force proportion ratio α of frame columns for each storey under static pushover analysis where ratio α equal to the shear force of columns divide storey shear force($\alpha=Q_C/$

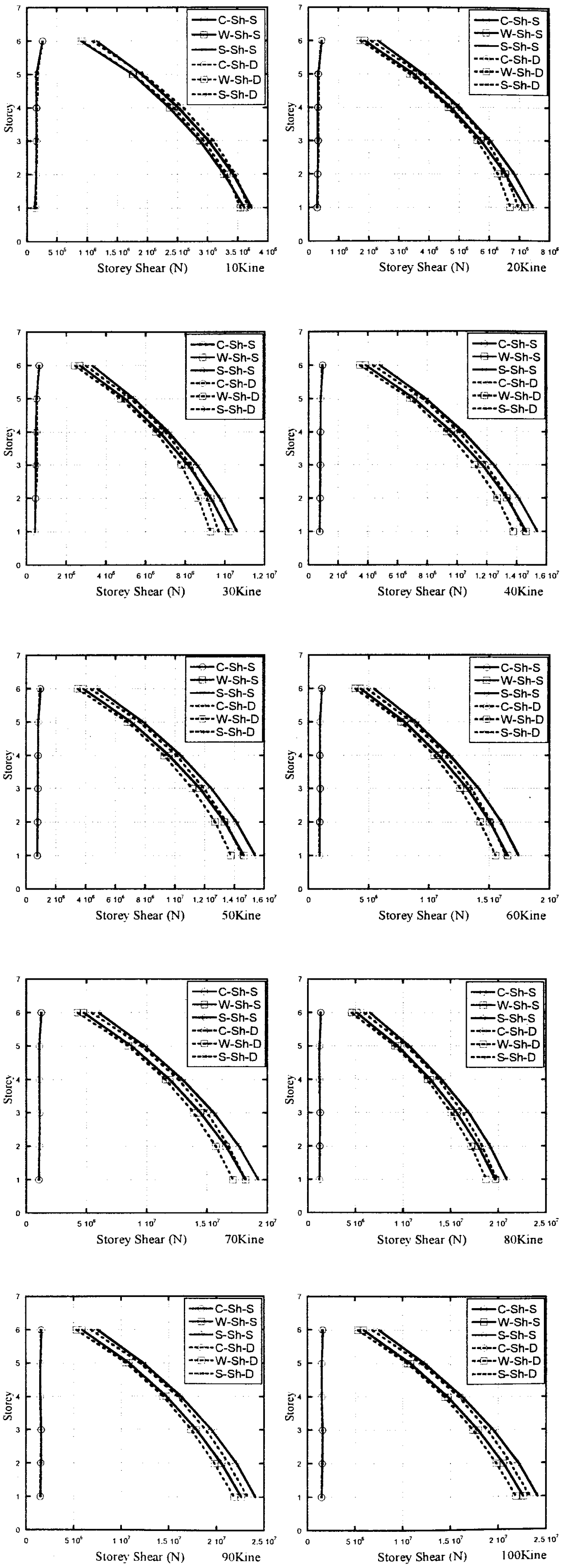


Fig.18 The interstorey shear force distribution of different intensity

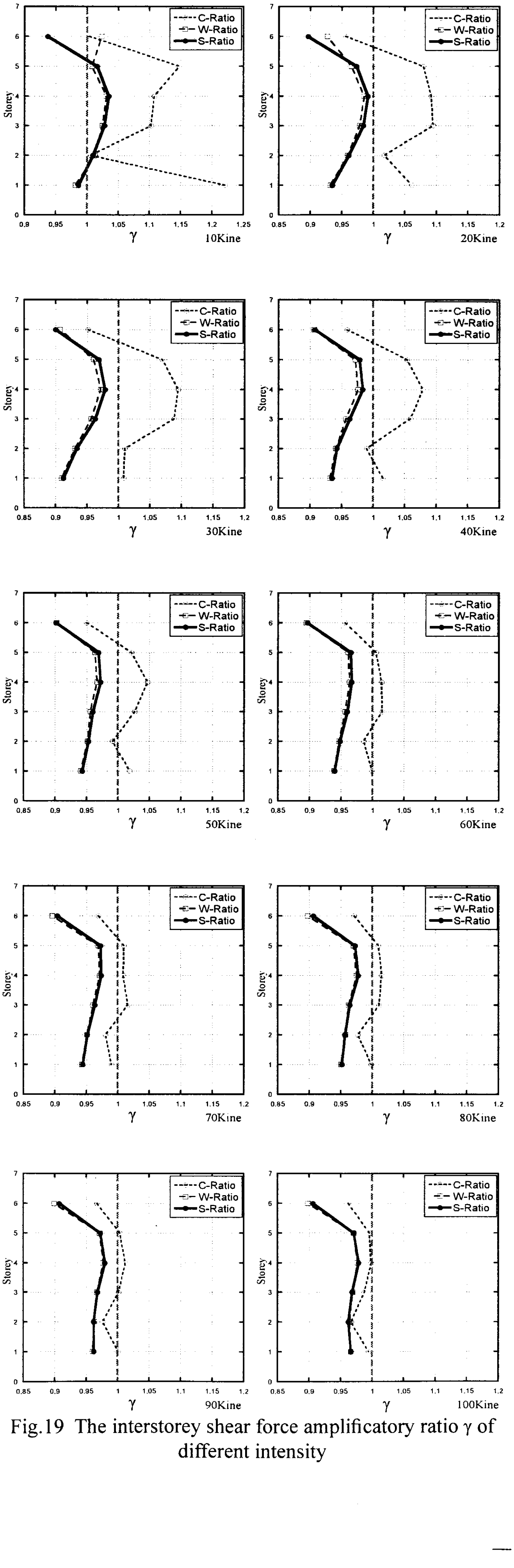


Fig.19 The interstorey shear force amplificatory ratio γ of different intensity

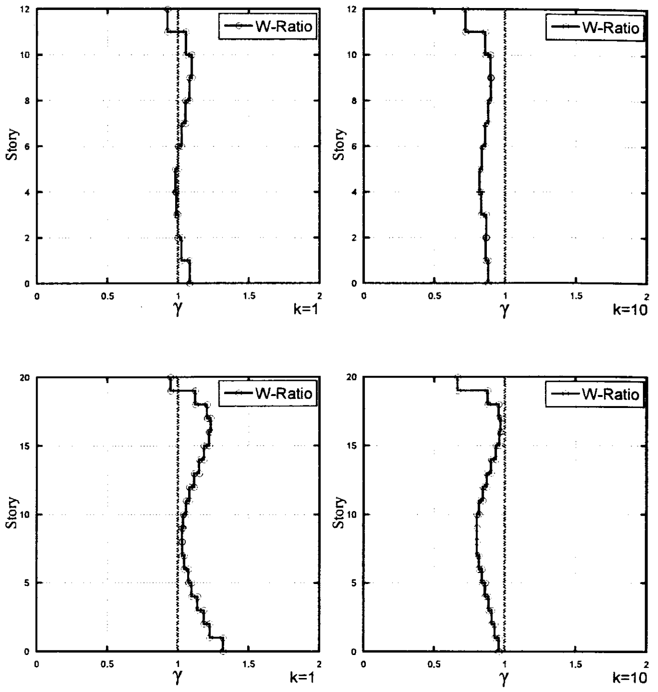


Fig.20 The interstorey shear force amplificatory ratio γ of 12 storey and 20 storey models

Q_{ST}), the proportion changes with storey drift angle, because the shear wall begin to crack and the stiffness minish, but the columns are still elastic, columns take more proportion of stiffness in each storey, so columns should take more shear forces. In Figs.15, 16, symbol D means dynamic analysis result, symbol S means static pushover analysis result, IDA means incremental dynamic analysis result if there have no special indication. Fig. 15 shows the maximal storey displacement of different intensity(Average result of twenty ground motions), we can see that the rule made before is viable, the deformation shape of the model under dynamic and static analysis perfectly match. Fig. 16 shows the storey drift angle of different intensity, there are some differences between them because of the high vibration mode shape and that the SDA for each storey doesn't reach the maximal value at the same time.

Fig. 17 shows the interstorey shear force for each storey under pushover static analysis and incremental dynamic analysis(IDA), Fig. 18 shows the interstorey shear force distribution of different incremental intensity, Fig. 19 shows the amplificatory ratio γ of different incremental intensity where the amplificatory ratio γ equals to dynamic shear force divide static shear force($\gamma = Q_D/Q_S$). In the legends, the first letter C, W and S mean column, wall and total storey respectively. We can see the behaviors of frame columns and core shear walls are very much different. The shear force of columns for each storey change smoothly, shear wall take a large part of shear force for each storey because of its large stiffness, the amplificatory ratio γ

is also different between columns and shear wall under different intensity, the ratio γ of the whole storey is almost less than 1 because of the wall affection, but the ratio γ of columns is almost larger than 1 and different in each storey.

The analytical model in this paper is a realistic frame model but the number of storeys is limited only by six. 12 storey and 20 storey analytical models are discussed in another paper [6]. The model is very simple one bay model, and the main parameters are different stiffness ratio k between core wall and columns, and different building height. Some results are shown in Fig. 20, the amplificatory ratio γ has a great connection with stiffness distribution between core walls and columns, especially the location of the ratio γ along the height of building is also very important. The influence of stiffness ratio k and building's height should be investigated by using more realistic model in the next research work.

4. Conclusive remarks

From the analytical results above paragraphs, we can get some valuable points of view to supervise the real practical design method as follows,

1. The rule to compare static and dynamic analysis is viable,
2. The proportion of shear force between columns and shear walls is changed in different SDA because of the stiffness proportion changed in elastic and plastic status,
3. The amplificatory ratio includes three aspects, the first is the intensity of the input ground motions, the second is that the stiffness ratio between RC core and perimeter frame will affect shear force amplificatory ratio, the third is the location in the height where the ratio is different at different part of the building.

In the future, we will think about changing the stiffness proportion between columns and core walls because that in real building plan they may have different numbers of columns and shear walls, on the other hand, we will change the analytical model to 12 storey, 20 storey and 30 storey to find the normal rules to supervise the real design work.

5. Acknowledgments

This research is a part of the international cooperative program of China-Japan research on seismic performance of hybrid structures of steel-concrete in the high seismic intensity region. Many investigators are involved in this program. A large number of numerical analysis will be done on the Japanese side by the nonlinear finite element analysis program of Prof. Kawano, and some large-scale experiments will be done on the Chinese side by Xi'an Architecture Technology University, they will analyses the hybrid structure system by Ansys too.

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